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TITLE- Fire Detection in Manned Spacecraft By Use of a Mass Spectrometer

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ABSTRACT

Although it is possible to minimize the combustion hazards aboard spacecraft, they cannot yet be totally eliminated. Thus, some mechanism for fire detection is needed. In Apollo the astronauts serve as the fire detection system since they are in close proximity to the equipment. However, astronauts will be less effective as fire detectors aboard the larger, more compartmentalized vehicles to be used in the future. For such vehicles an automated system to detect fires, preferably in their incipient stages, is desired.

The mass spectrometer, a chemical detector, seems the best candidate for giving rapid and reliable warning of an incipient fire. In addition, it can be integrated into a more general atmosphere monitoring system and coordinated with on board computers. Difficulties in its use are selection of sampling sites, identification of the location of the fire, reliability, and the determination of those chemical species most indicative of trouble. The use of more than one mass spectrometer would alleviate the sampling site difficulty. An overheat detector system coupled with the mass spectrometer as part of a more general failure detection system is one method of pinpointing the location of the fire and providing redundancy and increased reliability. The chemical problems appear to be the most difficult to handle at present and therefore extensive chemical investigations are needed.

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SUBJECT: Fire Detection in Manned Spacecraft by Use of a Mass Spectrometer - Case 320

DATE: May 20, 1969

FROM: M. V. Drickman

TM-69-2031-2

TECHNICAL MEMORANDUM

OUTLINE

This memorandum considers the need for fire detection devices for future manned spacecraft. It assumes that a device to detect fires in their incipient stages would add significantly to the safety of long term space flights. From a survey of currently available fire detectors, the mass spectrometer (a chemical detector) is judged the best because it has the capability to provide accurate, fast, and constant surveillance and warn of an incipient fire. An examination of the development problems to be expected in adapting a mass spectrometer to spacecraft use reveals no insurmountable problems.

THE NEED FOR FIRE DETECTORS

Recent fire prevention efforts in the Apollo program have resulted in extensive redesign of the spacecraft interior with rigid criteria used in the selection of materials. Materials with minimal flammability characteristics are employed except where only an available flammable material fulfills essential design requirements or the material is located in an area of low fire hazard. Necessary flammable materials are protected from the environment via a protective covering or other device. In spite of these efforts, however, the fire hazard has not been totally eliminated.

In Apollo the astronauts serve as the fire detection system. It is thought they will be able to see or smell impending trouble in the compact Apollo command and lunar module cabins. Human sensors as fire detectors appear less appropriate for Apollo Applications (AAP) missions and future planetary missions; the vehicles to be used will be much larger and more compartmentalized than Apollo vehicles. Thus, a reliable means of detecting fires, preferably in their incipient stages, is needed for advanced programs.

METHODS OF FIRE DETECTION

A simplified, qualitative description of the detectable changes occurring within an enclosure during a fire is given in Appendix A. Briefly, the fire progresses through two distinct phases: initial pyrolysis in which complex polymer molecules are decomposed, releasing volatile molecules from the matrix of the solid material, followed by combustion during which the gaseous molecules are oxidized. The time elements of each phase are a function of the imposed thermal stress and of the material properties. The pyrolysis process is in general endothermic, requiring external heat, while combustion is notably exothermic, hence supplying an excess of heat for continuation and broadening of the reaction. Thus, the most effective point of interruption is prior to the onset of the self-sustaining combustion phase. The pryolysis process is much more difficult to detect, however, because the changes to the enclosure's nominal pressure, temperature, and radiation environment are extremely small. Only the addition of new chemical species to the atmosphere represents a significant change of reference state. As combustion proceeds however, a wealth of other phenomena occur, including temperature and pressure rise, detectable radiation, and continued production of new chemical species.

A survey of currently available fire detectors was made, and is summarized in Appendix B. The fire detectors are discussed in terms of the fire-induced changes they detect. The major drawback with most of these detectors is that they work only in cases where a fire has already started. With the exception of the mass spectrometer, the devices that can detect an incipient fire lack sensitivity, rapid response, or the capability of constant monitoring. Thus, if these methods are employed extensive damage can occur before the fire is detected and extinguishing procedures initiated. Since even slight damage to a manned spacecraft could lead to fatal consequences, the mass spectrometer's capability to detect the fire in its initial pyrolysis stage makes it the outstanding candidate for spacecraft use.

A question which logically presents itself is: How does the effectiveness of a mass spectrometer compare with human sensors? While a direct comparison cannot be made, three significant differences are evident. We consider first human sensors. A potentially serious shortcoming is that some harmful gases are odorless, e.g., CO_2, hence cannot be detected by humans. Secondly, the ability to smell contaminants depends on the rate of their addition to the atmosphere. If the build up of a contaminant is slow, it is difficult for a human to detect initially and he tends to become desensitized to its presence. Thus he might not notice until it was present in significant amounts. Finally, wide variation between individuals does not allow us to set up guidelines based on human response data. Furthermore, on recent Apollo missions the astronauts suffered from colds, a condition which greatly decreases the ability to detect contaminants. On the other hand, the mass spectrometer which can reliably detect contaminants present at a level of one part per million (ppm),* can respond very rapidly, in some cases within a second or less. In addition to detecting contaminants and measuring their concentrations, it can determine rates of concentration changes. Thus, while a direct comparison cannot be made, we know that the mass spectrometer's capabilities exceed those of human sensors in several critical ways.

THE MASS SPECTROMETER

The mass spectrometer separates ions according to their masses, or, to be precise, according to their mass to charge (m/e) ratio. Neutral species must be ionized before they can be separated by the mass spectrometer. This is usually accomplished by bombarding molecules in the gas phase with electrons emitted by a filament. These electrons may either knock other electrons out of the molecule (formation of an ion), or they may decompose the molecule into charged fragments. These charged particles are then exposed to electric and magnetic fields within the mass spectrometer. A lens system focuses the ions into a beam which is directed into the analyzer where a special configuration of electric and/or magnetic fields separates the ions according to mass. The separate components of the beam are then collected and detected as current.

The mass spectrometer can be designed to detect both pyrolysis products and the build-up of other gases which may be harmful. Thus the mass spectrometer can meet the needs of both atmosphere monitoring and fire detection. It could be coordinated with on-line computers with output in any desired form thereby providing us with constant atmospheric surveillance.

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*The threshold for human detection of ethyl mercaptan, the most odorous substance known, is 0.016 ppm.[3] Other materials' detection thresholds lie above this, e.g., vanillin is considered aromatic at 294 ppm.[4]

CURRENTLY AVAILABLE MASS SPECTROMETERS

Mass spectrometers have until recently been used solely as large analytical tools in laboratories. Current use as flight instrumentation in airborne vehicles, however, has resulted in the development of small, rugged, and lightweight instruments.

Perkin-Elmer has developed several such lightweight mass spectrometers for NASA. Their SBA 1200 miniaturized mass spectrometers were designed and built for use by NASA in monitoring and analyzing the environment of the X-15 pilot. This device has two modes: monitoring and scanning. The monitoring mode monitors up to twelve positions simultaneously. The output can be set for either slow and sensitive response or very rapid and less sensitive response to changing conditions. The scanning mode sweeps the useful range of the mass spectrum. The useful mass range is defined as twice the resolution. For example, if the instrument can resolve mass 50 from 51 the resolution is defined as 50 and the useful mass range is about 100. From the scanning mode spectrum it is possible to compute the partial pressures of a number of species in addition to those measured in the fixed spectrum, i.e., the monitoring mode. The SBA 1200 can monitor twelve peaks which include H_2, CH_4, NH_3, H_2O, N_2, O_2, H_2S, CO_2, and COH, HC, and COOH fragments. (It is almost impossible to differentiate between CO and N_2 because their molecular weights are so close. However, ancillary equipment could remove this difficulty). In the scanning mode, m/e's from 2 to 100 are scanned in 45 seconds with a resolution of 45. The SBA 1200 weighs 47 pounds, has a power requirement of 28 V dc and 48W, and operates in a pressure range of 3 to 14.7 psi. With some modifications this instrument could serve as a spacecraft atmosphere monitor and fire detector.

Several other mass spectrometers could be adapted to spacecraft requirements. The Laboratory Contaminant Sensor (SPO #20213) was also developed for NASA by Perkin-Elmer. A series of three sorbent cells extract contaminants (human waste and off-gassing products of nonmetallic materials) from the ambient atmosphere at room temperature. The cells are then heated and the contaminants desorbed through a special inlet system to a mass spectrometer for identification and concentration determination.

The Perkin-Elmer PAA 104 Quadrupole Mass Spectrometer was designed for high altitude or planetary atmosphere analysis.

It can accurately measure the relative abundance of selected atmosphere constituents and output data in form for telemetering. This device employs an electric rather than a magnetic field for the separation of particles; therefore it does not require a heavy magnet. As a result it is low in weight (8 pounds). It would, however, require redesign for use in spacecraft.

A monitoring system has also been developed for potential use in AAP. The prototype can monitor for O_2, N_2, H_2O and CO_2 and can be modified to detect He, Ar, CH_3 fragments, and total hydrocarbons. The power requirement is less than 3.5W and the weight is under 7 pounds. It operates in the 4 to 44 mass range and provides an accuracy of $\pm$ 2% for N_2 and O_2 (for 30 days) and $\pm$ 5% for CO_2. There are no data available for water. This device, called the two-gas atmosphere sensor system, was designed by Perkin-Elmer to be Apollo compatible with regard to vibration and shock.

PROBLEMS ASSOCIATED WITH MASS SPECTROMETERS

Until recently the complexities of mass spectrometer data interpretation restricted the instrument to laboratory use. Present computer technology, however, has eliminated the necessity for a highly trained technician to operate the machine and interpret the data, thereby making spacecraft use of the mass spectrometer feasible. Direct data handling by onboard computers is preferred to telemetry. The time advantage that the mass spectrometer provides would be lost if telemetry were employed, especially in deep space missions; also there are periods during which telemetry is impossible.

Some of the elements involved in onboard data analysis are:

1. memory storage of information necessary for data reduction

2. automatic switching between monitoring and scanning modes after selected time intervals

3. calculation of concentration of about ten selected species

4. measurement of rate of concentration changes if species are detected in significant concentrations

5. storage of the above information if and when conditions dictate calculating projected concentrations

6. activation of alarm system when necessary

The level of computer usage depends on the number of species monitored, the frequency of monitoring, the quantity of data necessary to characterize each species, and other considerations related to the sophistications of the desired detection and evaluation mode.

Some remaining difficulties to be overcome include:

1. Sampling site determination and prevention of inlet tube clogging by the less volatile atmospheric contaminants.

2. Determination of those chemical species most indicative of trouble.

   a. Pyrolysis products resulting from reactions in an oxygen-containing environment.

   b. Contaminants arising from off-gassing of nonmetallic components.

   c. Contaminants arising from human waste products.

   d. Interaction of these species with the spectrometer, i.e. their chemical interactions with each other and their behavior in the ionization chamber of the spectrometer.

3. Identification of the exact location of the fire or incipient fire.

4. The level of the reliability of the information obtained from the mass spectrometer. Is it sufficient or should it be coupled with a back-up system?

Sampling site selection difficulties may be overcome by having more than one mass spectrometer and by using a system of sorbent cells as described in this memorandum. (This type of system would also simplify the problem of locating the fire.) The cells and inlet tubes would be placed at the sites of maximum fire hazard in the spacecraft. Short, wide inlet tubes would maximize the flow rate and minimize the condensation of the less volatile pyrolysis products and atmospheric contaminants.

The behavior of nonmetallic materials and the reactions occurring in the ionization chamber of the mass spectrometer constitute the two most difficult chemical problems. Nonmetallic materials in areas of fire hazard have to be thoroughly studied and the products of oxidative pyrolysis determined. Chemical reactions may occur in the mass spectrometer and the presence of actual pyrolysis products and atmospheric contaminants may be masked by the appearance of new species. The detector will inform us of these new species, but we may have no information about their chemical precursors. For these reasons, extensive chemical investigations are needed. The other chemical problems are not as difficult to handle. The problem of off-gassing can be eliminated if the materials are properly treated before they are installed in the spacecraft. Present data on human waste product accumulation in enclosures, made available by many groups of investigators, should offer a sufficient base for mass spectrometer calibration.

Although the mass spectrometer can warn of an incipient fire in a general area of the spacecraft, it cannot pinpoint the trouble. This is probably its major drawback. However, there could be a back-up overheat detector system coupled with the mass spectrometer. Overheat detectors could be placed at many potentially hazardous sites in the spacecraft and their output correlated with the mass spectrometer to determine the fire's location. Both the mass spectrometer and the overheat detector could be components of an overall failure detection system in the spacecraft. The data handling for the overheat detectors would be similar to that for the mass spectrometer.

The last major problem is that of reliability. There is always a doubt when we rely on only one method. No single method is capable of 100% reliability, and just as there is an extreme hazard if no detection system is used, the consequences of false alarms can be quite serious. A possible solution to this is to rely on redundancies. For example, couple the mass spectrometer with a back-up system which monitors some parameter other than the build-up of gaseous pyrolysis products. It is reasonable that the overheat detector could provide the required redundancy. If both the mass spectrometer and the heat detectors simultaneously yield positive responses we would be fairly certain that a real fire hazard exists. A great deal of work must be done before a system such as described can be implemented. However, the risk of fire, small though it may be, sees to justify undertaking a project such as outlined in this memorandum.

CONCLUSIONS

The fire hazard has not been totally eliminated from the Apollo command module, and will be present on future vehicles. Human sensors will be less effective fire detectors on these larger, more compartmentalized spacecraft. For these reasons, the design and implementation of an automatic fire detection system should be pursued.

Since even a small fire aboard a manned spacecraft could have fatal consequences, it is desirable to have a system capable of detecting a fire in its incipient stages. A system using mass spectrometers and overheat detectors is one possibility. The mass spectrometer would detect the presence of combustible gases in the atmosphere and the overheat detectors would aid in pinpointing the location of the trouble. This system would provide reliability, rapid response, sensitivity, a constant monitor, and could be incorporated into an atmosphere monitoring or overall failure detection system. The method appears feasible and should be further investigated.

M. V. Drickman

2033-MVD-tla M. V. Drickman

APPENDIX A

A QUALITATIVE PICTURE OF COMBUSTION

Detailed understanding of the processes involved in pyrolysis and combustion is beyond the present state of the art. Within the past few years, however, sophisticated experimental techniques have enabled us to answer some of the basic questions. A simplified, qualitative description of the changes resulting from pyrolysis and combustion in an enclosure is given here as a basis for understanding detection techniques.

Pyrolysis

The major fire hazard in spacecraft lies with non-metallic materials, specifically organic polymers. When these materials are heated they decompose (pyrolyze) releasing gases, hence changing the properties of the original material. For example, polymeric materials may undergo a noticeable color change or lose mechanical properties upon heating. The intital gaseous pyrolysis products introduced into the atmosphere do not usually cause a significant increase in the total pressure of the spacecraft interior; however, their concentrations, which may be to the order of parts per million, are detectable by instruments such as a mass spectrometer.

Combustion

If the pyrolytic production of gases continues, accompanied by increasing temperature and sufficient oxygen, ignition and propagation may occur. The major chemical reaction involved is the oxidation of the gaseous pyrolysis products. The combustion products are usually produced in excited electronic states and emit radiation when they decay into the stable ground states. We see a flame because of this radiation. If conditions are such that the reaction is self-propagating in an enclosure, there will be an increase in both the temperature and pressure of the system and new chemical species will appear. These new species consist of intermediate and final products of combustion, in addition to some very short-lived species known as reaction intermediates.

APPENDIX B

FIRE DETECTORS

The most significant physical and chemical changes occurring in an enclosure during a fire are:

I Emission of electromagnetic radiation

a. ultraviolet
b. visible
c. infrared

II Rise in temperature

III Rise in pressure

IV Production of new chemical species

a. combustion products
b. combustion intermediates

1. molecules
2. ions
3. free radicals

c. smoke

Fire detectors can be categorized according to which of these environmental changes they monitor.

I Radiation Detectors

a. Ultraviolet detectors

Ultraviolet radiation is emitted by arcs and flames. A differentiating capability can be built into ultraviolet detectors which enables them to provide unambiguous detection of a flame.

b. Infrared detectors

Infrared radiation is emitted by hot objects and flames. However, there are many infrared sources in normal environments and it is difficult to differentiate between the sources of radiation.

Both ultraviolet and infrared detectors are limited because they can only scan a limited area.

II Heat Detectors

These devices measure either the temperature or the rate of temperature change. For purposes of fire detection the absolute value of the parameter being measured may not indicate the fire hazard as accurately as the rate of change of the parameter. Several heat detectors are available. Some measure the rate of change of cabin atmosphere temperature and others monitor the temperature changes in electrical circuits. Although they have been used in aircraft for many years, their reliability remains low e.g., they frequently give false alarms. For this reason they cannot be considered for use by themselves in manned spacecraft. However, if heat detectors are part of detection systems which incorporate other sensors, they may be helpful in detecting incipient fires.

III Pressure Change Detectors

The presence of fire is only one of several things which can cause rapid pressure rise in an enclosure and not all fires will cause a detectable rise in cabin pressure. Furthermore, pressure change detectors have a slow response time.

IV Chemical Detectors

Instruments which monitor the concentrations of chemical species may also be employed in fire detection. For example, significant increases in the concentrations of CO and CO_2 indicate that a fire has already broken out. Alternatively, the presence of certain combustible compounds in the atmosphere may be used as a warning for impending fire. There are several ways of detecting these chemical species.

a. Infrared absorption techniques

The nondispersive infrared analyzer can be used to detect combustion products and intermediates. However, it cannot detect certain chemical species and may be employed only in the localized detection of fires because the detector can scan only a limited area.

b. Condensation nuclei detector

This device, sensitive to particles in the size range of 2×10^{-3} to 5×10^{-1} microns, has the ability to detect incipient fires. It does not give adequate warning, however, and could give false alarms.

c. Ion detectors

Ions are fairly long-lived combustion intermediates and are detectable during a fire. However, they are not present during the incipient stages of a fire.

d. Combustible gas detector

Also known as a catalytic burner, this has been used in aircraft for many years. It does not detect fire, but rather indicates that a fire may occur if an ignition source is introduced. The device operates by catalytically initiating the combustion of an atmosphere sample placed in a sealed compartment, thereby determining whether a reaction between oxygen and other atmospheric constituents can take place. In addition to detecting H_2 and CO, the combustible gas detector detects the build-up of many toxic, combustible gases. The major difficulties with this device are that it is relatively insensitive to CO and does not provide a constant monitor.

e. Gas chromatographs

These instruments separate and identify atmospheric constituents. However, they do not operate as continuous monitors and their response time is relatively long.

f. Mass spectrometers

These appear to be the best devices for detecting chemical species. They are inherently fast, accurate in the determination of partial pressures, and extremely rugged. Further, they operate well regardless of gravity conditions, and provide a continuous monitor.

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